MOVE-III: AN IN-SITU DETECTOR TO SUPPORT SPACE DEBRIS MODEL VALIDATION

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ABSTRACT

In-situ measurements of sub-millimetre space debris and meteoroids can be acquired with different means and technologies, including impact detectors, opportunistic returns from space-exposed material, as well as photographic surveys. MOVE-III is a CubeSat project of the Department of Aerospace and Geodesy at the Technical University of Munich, designing and developing a CubeSat bus that will carry three in-situ space debris and meteoroid active impact detectors. The mission aims at supporting the validation of the small object population of space debris models and the characterisation of the space debris environment in Low Earth Orbit, by providing measurements of the mass, velocity, and rough direction of sub-millimetre space debris and meteoroid impactors. The main payload of MOVE-III consists of an assembly of plasma ionisation DEDRA (DEbris Density Retrieval and Analysis) sensors, carried on a 6U Platform.

Keywords: Space debris; MOVE-III; Impact detection.

1. INTRODUCTION

Since the beginning of the space age in 1957, numerous artificial objects have accumulated in orbits around the Earth, travelling at different altitudes and orbital planes. Space debris poses a growing hazard to operational space missions and hinders the future of humanity's safe use of space. While a portion of the defunct objects are large enough to be tracked by surveillance networks, the vast majority is non-trackable debris; the result of rocket launches, break-up events, accidental or deliberate collisions and explosions, and deterioration of spacecraft components. Within the past decades, several models have been developed, aiming at modelling the ever-changing space debris and meteoroid environment. Space debris and meteoroid models are often essential tools for spacecraft designers and operators, as they can support the risk assessment studies which are becoming an integral part of the mission design and development phases.

The characterization of the space debris environment is not an easy task, especially when the non-trackable population is considered. Whilst on-orbit remote sensors have the potential of detecting non-catalogued objects, at present, the sub-millimetre realm can only be effectively studied with in-situ impact techniques. Models such as ESA's MASTER (Meteoroid and Space Debris Terrestrial Environment Reference) and NASA's ORDEM (Orbital Debris Engineering Model) depend on in-situ, sample measurement data to validate their small object population estimates.

In the paper, past and current missions and experiments dedicated to impact detection are listed, and the future MOVE-III CubeSat mission is introduced. The payload of MOVE-III, as well as the expected mission data products are presented. Results from the impact flux analysis performed with MASTER are additionally discussed.

2. IMPACT DETECTION BACKGROUND

In-situ measurements of sub-millimetre space debris and meteoroids can be acquired with different means and technologies. Impact detectors are often classified as either passive or active [1, 2, 3, 4]. Opportunistic analyses of returned surfaces with a different primary goal, as well as photographic surveys are additionally considered [3, 4].

Passive detectors are dedicated collection surfaces, exposed to the space environment for a period of time and brought back to Earth for analysis. The cumulative number of impacts on the returned surface can be measured, and the likely particle residues can be chemically analysed to determine the impactor's composition. Passive detectors are typically characterised by large areas and low system complexity, however, they require a sample

Proc. 8th European Conference on Space Debris (virtual), Darmstadt, Germany, 20–23 April 2021, published by the ESA Space Debris Office
Ed. T. Flohrer, S. Lemmens & F. Schmitz, (http://conference.sdo.esoc.esa.int, May 2021)

return mission. The detectors flown so far had limited orbital coverage and time of exposure. Examples of passive detectors were specifically designed surfaces and experiments on the Long Duration Exposure Facility (LDEF) [5, 6, 7, 8] and the Mir space station [9, 10, 11, 12].

Active detectors are impact detection instruments, flown on-board satellites, launchers or space stations. They typically employ a more complex measurement system to acquire time-dependent impact measurements and transmit them to the ground. The first active detectors were designed to measure meteoroids and cosmic dust. Active detectors can measure impact flux, velocities, and possibly particle mass, size and impact direction, depending on the sensor design and the technology used. However, they seldom incorporate chemical composition analysis systems, they are characterised by a small surface and they usually provide measurements limited to small particle size ranges. Based on the technology used and their measurement acquisition principle, active impact detectors can further be classified into subcategories. Example detectors include piezoelectric, acoustic, resistive, plasma ionisation, PVDF and capacitive discharge. More complex active detectors include chemical and spectrum analysers and optical photometers [1]. Active detectors that have flown on-board spacecraft include the Geostationary Orbit Impact Detector (GORID) [13, 14], the Debris In-Orbit Evaluator (DEBIE) [15, 16, 14], the Munich Dust Detector (MDC) [18, 19, 20, 21] and the Space Debris Sensor (SDS) [22].

Opportunistic studies and analyses have also been performed on space-exposed hardware and surfaces that were recovered but were not specifically designed to collect impacts. The analysis of opportunistic returns can provide supplementary measurements of the space debris and meteoroid environment, however this is typically more complicated, as the returned materials were primarily designed to serve another function. Examples of such returns include the solar panels and the Wide Field Planetary Camera 2 (WFPC-2) from the Hubble Telescope [23, 24, 25, 26], the European Retrievable Carrier (EuReCa) [23, 27] and the Space Flyer Unit (SFU) [28].

Except for detectors and opportunistic returns, the contribution of studies with digital cameras and photographic surveys should additionally be considered. Surveys were performed on the ISS and the Mir space stations [29, 30, 31]. Determination of very small features (<1 mm in diameter) with imagery is however usually difficult [29].

Examples of passive and active detectors, as well as opportunistic returns are presented in Tab. 1, Tab. 2, Tab. 3 respectively.

3. PROJECT DESCRIPTION

Space debris and meteoroid models like ESA's MASTER typically rely on passive detectors or opportunistic returns to validate their small object population estimates. The small particle validation of MASTER has been performed using measurement data from the Long Duration Exposure Facility (LDEF), the returned solar arrays of the Hubble Space Telescope and the European Retrievable Carrier (EureCa) [49]. Observations from active in-situ detectors have yet to be considered in the validation process of the MASTER model. For the case of MASTER, the consideration of data from active detectors can:

- help filling in the data gap of the small object population of space debris models,
- provide a link to larger size regimes by means of data fitting.

Taking into account that the small space debris population is an important contributor to the degradation of material and equipment in space, data from in-situ sensors can further support material degradation studies as well as shield design and testing.

3.1. MOVE-III

MOVE stands for Munich Orbital Verification Experiment. The MOVE project series started in 2006, within the Chair of Astronautics (LRT) of the Technical University of Munich, with support from the Scientific Workgroup for Rocketry and Spaceflight (WARR). The project team consists of Bachelor's, Master's and PhD students from various departments of the university. The MOVE team has developed, tested and operated three CubeSats, with the first launch of First-Move in 2013, the second launch of MOVE-II in 2018 and the third launch of MOVE-IIb in 2019 [50]. The team is also working on the development of High Altitude Pseudo Satellites (HAPS), as an experimental and testing platform for its future satellite missions.

MOVE-III officially kicked-off in May 2020, following the foundation of the new Department of Aerospace and Geodesy of the Technical University of Munich. The mission aims at supporting the validation of the small object population of space debris models, by providing measurements of the mass, velocity, and direction of sub-millimetre space debris and meteoroid particles. The main payload of MOVE-III consists of an assembly of plasma ionisation DEDRA (DEbris Density Retrieval and Analysis) sensors, carried on a 6U Platform. The design of the DEDRA sensor is based on the legacy of the MDC (Munich Dust Counter) and the lessons learnt from the missions that carried the heritage instrument on-board.

3.2. DEDRA Payload

The objective of the DEDRA detector is to measure the velocity and mass of artificial space debris and meteoroids in Low Earth Orbit (LEO), and thus contribute with measurements to the characterization of the space debris environment and the validation of space debris models. The sensor is based on the design of the Munich

Table 1. Examples of in-situ passive detectors. 'M' indicates that the primary detector objective is the observation of meteoroids and cosmic dust. 'De' indicates that the primary detector objective is the observation of space debris

Mission	Detector	Deployment date	Retrieval date	Orbital regime	M/De	Ref.
LDEF	CME (A0187-1)	1984 Apr 07	1990 Jan 12	482 - 340 km	M	[5]
LDEF	MAP (A0023)				M/De	[6]
LDEF	SIMS (A0187-2)				M/De	[7]
LDEF	SDIE (S0001)				M/De	[8]
Mir	Aragatz/Echantillons	1988 Dec 09	1990 Jan 11	425 - 350 km	M/De	[9, 10]
Mir	ESEF	1995 Oct 20	1996 Feb 08		M/De	[11, 12]
Mir	MEEP	1996 Mar 27	1997 Oct 01		M/De	[12]
Mir	PIE	1996 Jun 06	1997 May 24		M/De	[9, 10]

Table 2. Examples of in-situ active detectors. 'M' indicates that the primary detector objective is the observation of meteoroids and cosmic dust. 'De' indicates that the primary meteoroids objective is the observation of space debris

Mission	Detector	Experiment start date	Experiment end date	Orbital regime	M/De	Ref.
HEOS 2	DD	1972 Jan 31	1974 Aug 05	Highly elliptical Earth orbit	M	[32]
LDEF	IDE/MOS	1984 Apr 06	1990 Jan 14	482 - 340 km	M	[33]
Galileo	DDS	1989 Oct 18	2003 Sep 21	Interplanetary cruise to Jupiter, Jupiter orbit	M	[34, 35]
Hiten	MDC	1990 Jan 24	1993 Apr 10	Highly elliptical Earth orbit	M	[17, 18]
Ulysses	DUST	1990 Oct 27	2009 Jun 30	Heliocentric orbit	M	[36]
BremSat	MDC	1994 Feb 09	1995 Feb 12	350 km	M/De	[18, 19]
Express-2	GORID	1996 Sep 26	2002 Jul 17	Geostationary orbit	De	[13, 14]
Cassini-Huygens	CDA	1997 Oct 15	2017 Sept 15	Interplanetary cruise to Saturn, Kronocentric orbit	M	[37]
Nozomi (Planet-B)	MDC	1998 Jul 04	2003 Dec 09	Heliocentric orbit	M	[20, 21]
PROBA-1	DEBIE-1	2002 Aug	Present	677 - 553 km	De	[15, 14]
Cosmos-3M upper stage	MDD	2005 Oct 27	-	700 km	M/De	[38, 39]
EuTEF, Columbus/ISS	DEBIE-2	2008 Feb 07	2009 Sep 11	410 km	De	[16, 14]
EuTEF, Columbus/ISS	SODAD/MOS	2008 Feb 07	2009 Sep 11	410 km	M/De	[40, 41]
IKAROS	ALADDIN	2010 Jun 30	2011 Oct	Interplanetary cruise between 0.7 - 1.1 AU	M	[42]
Aquarius (SAC-D)	SODAD/MOS	2011 Jun 10	2015 Jun 08	653 km	M/De	[43]
Spektr-R	MDD3	2011 Jul 18	2019 May 30	Highly elliptical Earth orbit	M/De	[44]
TechnoSat	SOLID	2017 Jul 14	Present	590 km	De	[45, 46]
Columbus/ISS	SDS/DRAGONS	2018 Jan 01	2018 Jan 27	410 km	De	[22]
BepiColombo	Mio/MDM	2018 Oct 20	Present	Interplanetary cruise to Mercury	Me	[47]

Table 3. Examples of opportunistic returns

Mission	Surface(s)	Deployment date	Retrieval date	Orbital regime	Ref.
Solar Max	Thermal blankets, louvers	1980 Feb 14	1984 Apr 10	570-500 km	[48]
EuReCA	Thermal blankets, plates, solar arrays	1992 Jul 31	1993 Jul 01	508 km	[27]
Hubble Telescope	Solar arrays	1990 Apr 24	1993 Dec 08	600 km	[23]
Hubble Telescope	Solar arrays	1993 Dec 04	2002 Mar 03	600 km	[24, 25]
Hubble Telescope	Wide Field Planetary Camera 2 (WFPC2)	1993 Dec 04	2009 May 24	600 km	[26]
Space Flyer Unit	Thermal blankets, radiators, louvers, scuff plates	1995 Mar 18	1996 Jan 13	480 km	[28]

Dust Counter and uses the same measurement principle of particle impact ionisation. All electronic components are currently being re-designed, and an advanced version of the sensor is additionally proposed.

3.2.1. MDC heritage

The Munich Dust Counter (MDC) was a scientific space experiment that flew on board three different missions between the period 1990 and 2003, with the objective of measuring cosmic dust particles based on the principle of impact ionization. The MDC consists of an electronics box and a sensor box, with all five inner walls of the sensor box plated in gold and acting as a target area for the impacting particles (Fig. 1).

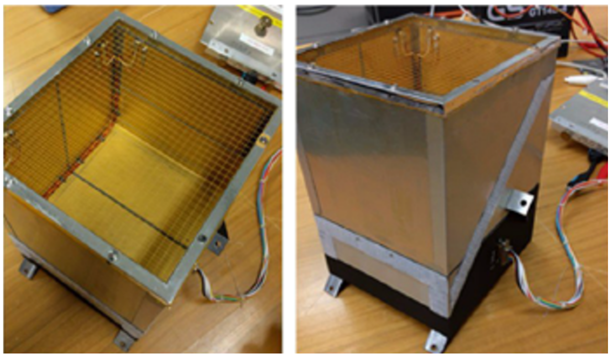

Figure 1. Engineering model of the Munich Dust Counter at the Technical University of Munich

The first satellite that carried the instrument on-board was Hiten, a Japanese satellite launched on January 24, 1990 and put into a highly elliptical orbit around the Earth. During the two years of operation of Hiten, 203 and 145 events were evaluated in the first and second year respectively. The evaluation involved the determination of the charge signals, amplitude and risetime. The derivation of the mass and velocity of the impacted dust particles was based on the procedure described in [51, 52].

The second satellite that carried the MDC on-board was BremSat, a small scientific satellite built by the University of Bremen's Center of Applied Space Technology and Microgravity (ZARM). BremSat was carried in orbit by a Space Shuttle on February 3, 1994 and was deployed in its initial 350 km high circular orbit a few years later. It re-entered Earth's atmosphere on February 12, 1995. The dust detection experiment focused at improving impact data of both meteorites and artificial debris. The MDC experiment on BremSat was not as successful as its predecessor, as it suffered from troublesome data analysis due to interferences [53], indicating the need for a sophisticated signal screening.

An improved version of Hiten and BremSat detectors flew on-board the Japanese Mars mission Nozomi. Nozomi was launched on July 4th 1998, and its mission ended on December 9, 2003. Initially, Nozomi was to be inserted into a highly eccentric Mars orbit, however, a series of unfortunate events resulted in Nozomi failing to enter the planned orbit around Mars and the mission was abandoned in December 2003. While the spacecraft might have never entered the intended Mars orbit phase, the improved MDC on-board Nozomi delivered a considerable amount of impacts during the early phases of the mission [20, 21].

3.2.2. The DEDRA sensor

Similar to the MDC, the DEDRA sensor consists of a sensor box and a compartment for front-end electronics. The sensor box has an effective aperture of approximately 80 x 80 mm^2, in order to be accommodated within 1U of the CubeSat. Two grounded grids are placed at the opening of the box, in order to shield the sensor from electromagnetic fields. In the upper half of the sensor, two collector plates with a potential of +/- 100 V are located (Fig. 2). The inner walls and backplate of the sensor are coated in gold, which is a suitable material due to its high atomic mass and chemical stability, and have a 0 V potential with

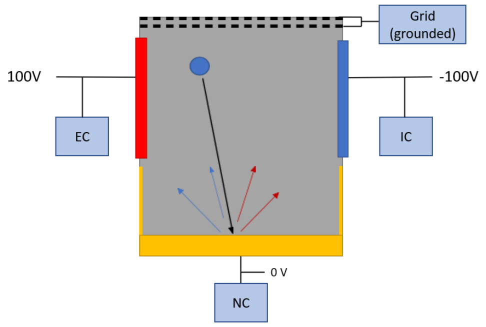

Figure 2. Baseline sensor design

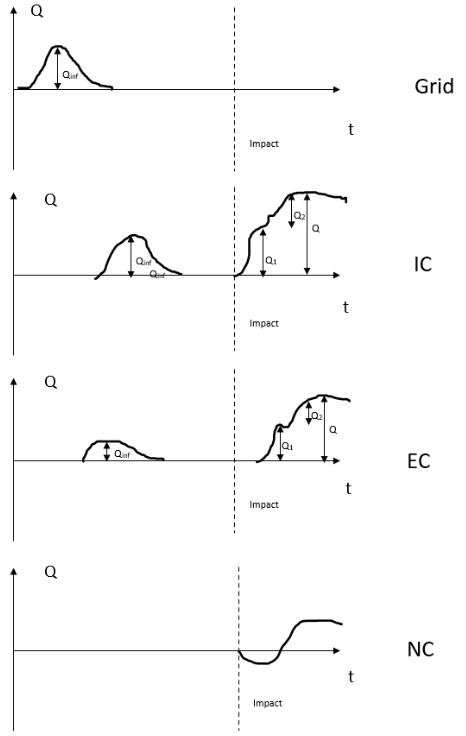

Figure 3. Signals on the four different channels for the baseline design

respect to the satellite structure (neutral channel). The two collector plates are connected to two separate charge amplifiers (electron channel, ion channel) while the entrance grids and the inner walls and backplate are connected to another amplifier (neutral channel). When an impact occurs on the gold-plated walls or the backplate of the sensor, plasma is generated and collected by the two charged plates. The positively charged plate collects the electrons (EC plate), whilst the negatively charged plate collects the ions (IC plate) from the plasma cloud. From the total charge and risetime of the signal on those channels, we can estimate the mass and the velocity of the particle by means of comparison with calibration signals which will be recorded using a particle accelerator facility. The impact is expected to generate an additional signal on the neutral channel, which can be used to derive the time when the particle hits the sensor box. This additional signal improves the velocity estimation and helps distinguishing noise from a true signal. Signals from the four channels are plotted as charge curves, such as those shown qualitatively in Fig. 3.

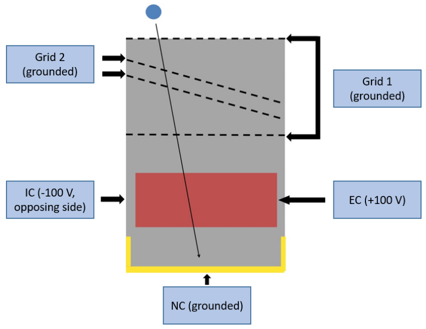

Figure 4. Advanced sensor design

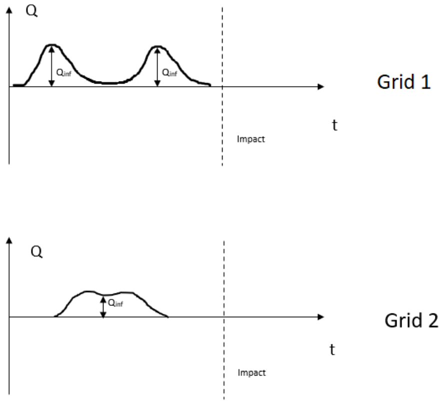

Figure 5. Signals on the two additional grids channels for the advanced design

While the observation principle for the derivation of mass and velocity is well established, the estimation of the particle's incident direction requires more complex considerations. Directional distribution analyses have been performed for Hiten's MDC data, however, a significant number of impacts from all directions of interest is required to derive good statistics. In order to improve the DEDRA's directionality readings, an advanced sensor design is proposed (Fig. 4). The advanced sensor design employs an a longer sensor box with two additional tltied grids that are connected to a common charge amplifier. This channel obtains two additional timestamps respecting another virtual plane (Fig. 5). Thus, a fifth channel for measurements is added. With this additional signal it is possible to compute two possible incident vectors. With the fly-by influence signal on EC and IC, the correct vector can be selected.

The DEDRA sensor can measure masses within the range of 10^{-15} kg and 10^{-10} kg and velocities up to 30 km/s. Calibration of the sensor is planned to be performed in the near future, using a particle accelerator facility.

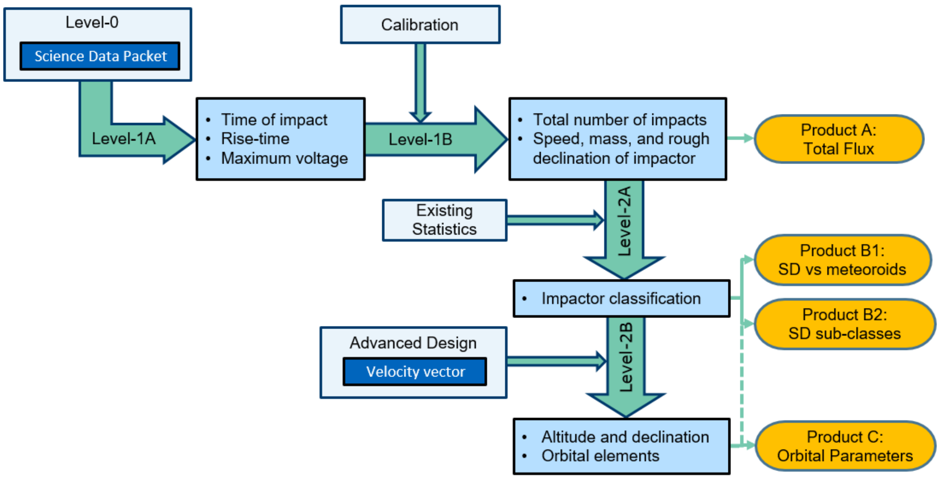

Figure 6. Data processing levels

3.3. Data Products

In many cases, data acquired from active in-situ detectors require sophisticated on-orbit and/or on-ground data processing, in order to eliminate the measurement noise from various sources (e.g. solar radiation, atmosphere, electronics etc.) and derive quantities that can efficiently be used for further analyses, including the validation of a space debris and meteoroid model. The lack of sufficient data-processing has rendered some of the already acquired datasets difficult to use (e.g. BremSat [53]), therefore, particular attention is planned to be given to both the sensor design and the post-processing of the impact observations.

For the purpose of providing products that can easily be incorporated in the validation procedure, a data processing chain has been defined. The chain is consisted of five different processing steps, from Level-0 to Level-2B (Fig. 6). The Level-0 processing step refers to all processing done on board. Level-0 produces a Science data packet which is downlinked from the satellite. With the input of the Science Data Packet, Level 1A processing outputs the time of impact, the signal rise time and the maximum voltage. This output is then used as input for the Level-1B processing. With the help of the calibration parameters, the total number of impacts as well as the speed, mass and the rough incidence angle of the impactor (using the baseline design) can be derived. Level-1B produces then the first of the deliverable products, which is the total flux of objects encountered during the mission lifetime. Further processing is planned, namely Level-2 processing, however this is still at an early stage. Level-2 processing involves a first level classification between space debris and meteoroids using existing velocity and distribution statistics as well as a second level classification between the different space debris sources. Using the full velocity vector that the advanced sensor design is expected to provide, an orbit integration for the determination of the orbital parameters of the impactors might also be possible.

4. MISSION CONSIDERATIONS

MOVE-III is being designed as a 6U CubeSat, with dimensions 30 x 20 x 10 cm. Three DEDRA sensors are planned to be accommodated in the platform, out of which two will use the basic design and one the advanced design (Fig. 7). All detectors will be positioned such that they face the flight direction at all times, as this is the direction with the highest incoming flux.

The nominal mission lifetime is planned to be 1 year. For power supply reasons, a sun-synchronous orbit will be preferred. ESA's DRAMA 3.0.4 (Debris Risk Assessment and Mitigation Analysis) and MASTER-8.0.2 have been employed to decide on a likely orbital altitude range that would maximise the flux of small debris and meteoroid particles, minimise the danger from small space debris that exceed the sensor's measurement capabilities, and ensure compliance with the space debris mitigation guidelines (de-orbit from the LEO protected region within 25 years).

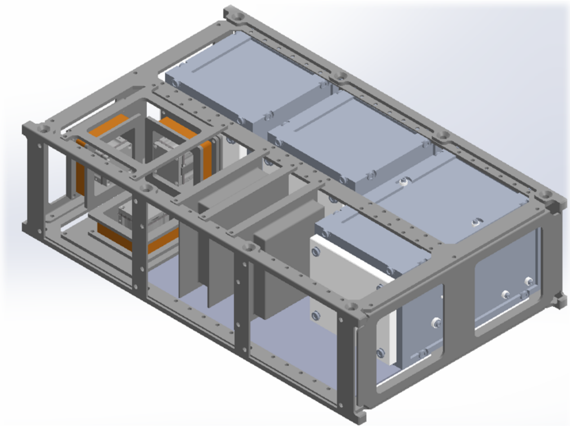

Figure 7. Accommodation of the DEDRA sensor on the MOVE platform

4.1. Expected Space Debris and Meteoroid Flux

In order to get an estimate of the particle flux likely to be encountered during the mission's lifetime, simulations have been performed with ESA's space debris and meteoroid MASTER model.

All simulations were run for the period of one year, for altitudes between 500 and 700 km. The selected simulation years cover the timespan between 2022 and 2027, as MOVE-III is expected to be launched within the next couple of years. The impactors considered by MASTER are all space debris objects and meteoroids that belong in the sensor's trackable mass range (10^{-15} kg and 10^{-10} kg). Assuming aluminium density and spherical impactors, the trackable mass range corresponds to objects with approximate diameter between 1 and 40 μm. MASTER's condensed population files were used for the modelling of the space debris objects while the Grün model with a Taylor velocity distribution is employed for the modelling of the meteoroids.

Reflecting the space debris environment LEO, the small object population is characterised by an increasing flux with increasing altitude (Fig. 8). The lowest flux is predicted for the year 2023-2024 and 500 km (126 impacts on 3 sensors), while the highest flux is predicted for the year 2026-2027 and 700 km (261 impacts on 3 sensors). With the current system configuration, the CubeSat's cross section in the flight direction will be 300 cm^2. While orbits with high flux are optimal for the acquisition of a considerable number of measurements, a trade-off between orbital heights with high flux and orbital heights from which de-orbiting within 25 years is possible is required. Simulations with DRAMA/OSCAR indicate that a timely re-entry without a de-orbiting device will not be possible for orbital altitudes that exceed 600 km. As the use of a de-orbiting device is expected to complicate the CubeSat design and introduce an additional post-mission disposal risk, MOVE-III is likely to fly between 500 and 600 km, and therefore collect up to approximately 214 impacts during the period of one year with high debris and meteoroid flux.

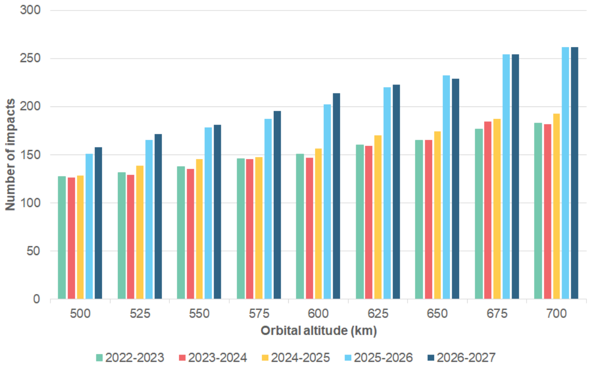

Figure 8. Evolution of space debris and meteoroid flux: number of impacts on 3 sensors per year

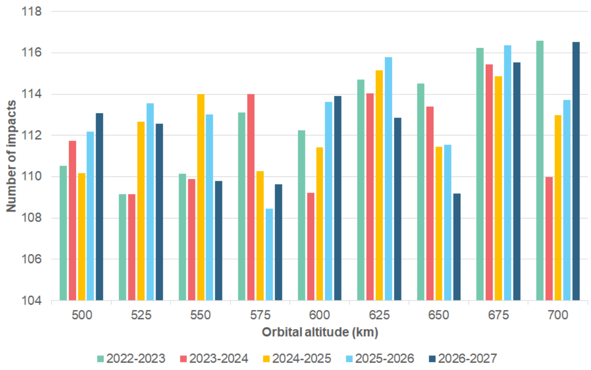

Figure 9. Evolution of meteoroid flux: number of impacts on 3 sensors per year

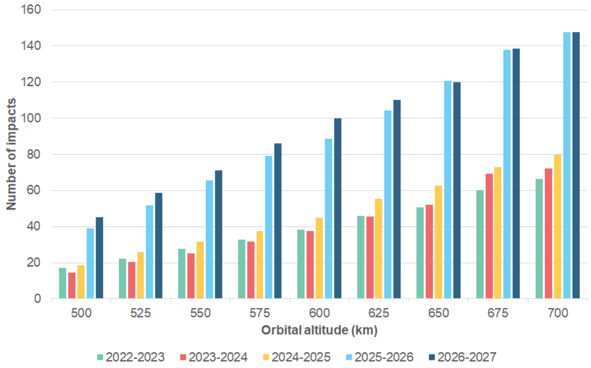

Figure 10. Evolution of space debris flux: number of impacts on 3 sensors per year

The individual contribution of the meteoroid population (Fig. 9) and the space debris population (Fig. 10) in the total flux estimates has additionally been investigated. As expected, the steadily increasing pattern is a characteristic of the space debris flux. The meteoroid flux on the other hand side follows a different distribution pattern, nevertheless sees a slight increase with increasing orbital altitudes. An interesting aspect of the space debris flux increase concerns the two last years of the simulations, where a sudden increase in the flux can be observed. This behaviour may be explained by analysing the contribution of the individual space debris sources considered by MASTER.

4.2. Expected Space Debris Sources

MASTER incorporates the following space debris sources [49]:

- explosion fragments,
- collision fragments,

- launch/mission related objects,
- sodium-potassium alloy (NaK) droplets,
- solid rocket moter (SRM) slag,
- solid rocket moter (SRM) dust,
- paint flakes,
- ejecta,
- multi-layer insulation (MLI).

The model allows the evaluation of the contribution of each space debris source individually. Simulations have therefore been performed for each of the aforementioned debris sources, for the orbital altitudes and mission years considered in the previous examples. Based on MASTER's output, the main debris source MOVE-III is expected to encounter is ejecta (Fig. 11), followed by solid rocket motor dust (Fig. 12) and paint flakes (Fig. 13). No NaK droplets, launch/mission related objects or MLIs are expected to be encountered, while the numbers of explosion and collision fragments as well as the SRM slag numbers are very low.

An interesting aspect of the contribution of the two main expected sources (ejecta and solid rocket motor dust) involves the evaluation of the driver of the increase/decrease of the respective population estimates. For the case of ejecta, the influence of the solar activity is a prominent factor in the fluctuations of the flux as the lowest numbers are observed during the year 2023-2024 which coincides with the next predicted solar maximum considered by MASTER. The picture is different for the case of SRM dust, whose flux may be sensitive to individual firings that could be affecting the estimates during certain years (e.g. 2025-2026). The fluctuations in the ejecta population indicates the benefit of targeting a low solar activity period for the launch and operation of MOVE-III, while potential future SRM activity in the vicinity of the CubeSat's orbit may further supplement the targeted data set with a considerable amount of measurements.

5. CONCLUSION

MOVE is a CubeSat project at the Technical University of Munich. The objective of the MOVE-III mission is to acquire in-situ measurements of submillimetre space debris and meteoroids in LEO, with the aim of supporting the characterization of the space debris environment and the validation of space debris models like ESA's MASTER. Three active in-situ sensors are planned to be carried on board. All sensors operate on the principle of impact ionisation and can provide measurements of the mass, the velocity and, with the advanced sensor design, the direction of the impacting particles.

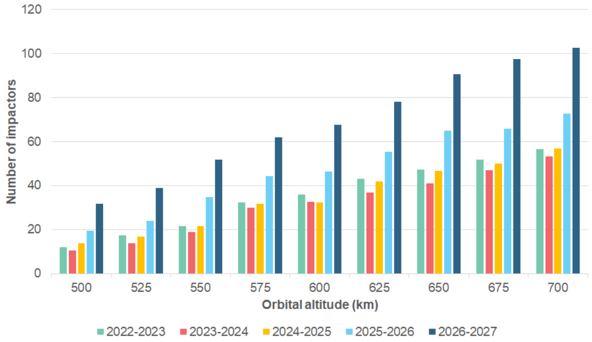

Figure 11. Evolution of ejecta flux: number of impacts on 3 sensors per year

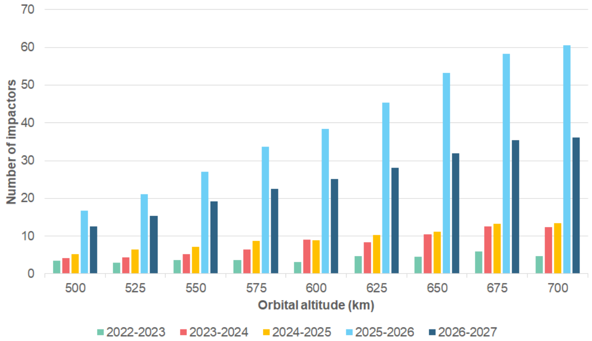

Figure 12. Evolution of solid rocket motor dust flux: number of impacts on 3 sensors per year

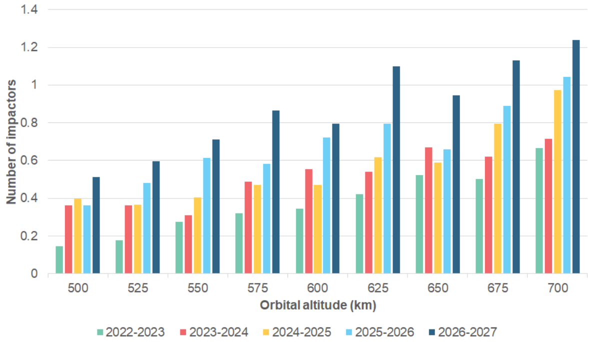

Figure 13. Evolution of paint flakes flux: number of impacts on 3 sensors per year

The MASTER model has been used to predict the space debris and meteoroid flux the CubeSat will encounter in the targeted orbital altitude range during the likely operational time period of the mission. MOVE-III is expected to fly between 500 and 600 km and, based on the simulations with ESA's MASTER model, collect a few hundred space debris and meteoroid impacts within one year of operations. The flux of small space debris and meteoroids is predicted to increase with increasing altitude and decreasing solar activity. SRM activity in the close vicinity of the satellite orbit might further benefit the collection of a considerable amount of impacts.

ACKNOWLEDGMENTS

The authors would like to thank Simona Iorgulescu for her valuable input in the MASTER simulations, Eleftherios Karagiannis for the joined management of the MOVE Science team, Paul Pucknus, Luis Pretsch and Mihai Schipor for their work on the sensor design, Marius Schlaak and Daniel Orozco for their work on the data processing chain and Maximilian Vovk for his work on the sensor and satellite bus risk assessment. We would like to express out gratitude to Ralf Srama, Ralf Münzenmayer and all the reviewers that took part in our System Definition Review. Special thanks go to Detlef Koschny, for introducing us to the history of the MDC and for supporting the DEDRA team since the very beginning, and to all current and past university students and staff involved in the MOVE and DEDRA projects: without your contribution and continuous support, this work would not have been possible.

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